The Relationship between Atmospheric Temperature, Fuel Volatility, and Engine Performance

By

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Motor-Fuel Volatility[1]

II—Starting Volatility[2,3]

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In the first paper of this series, published previously (2, Part I), equilibrium volatility was defined and a satisfactory method was described for its determination. In the papers comprising the present group, motor-fuel volatility has been interpreted in terms of engine performance.

The second paper of the series, which is the first of the present group, relates equilibrium volatility to ease of starting as determined by actual engine tests. The third paper defines effective volatility under driving conditions and indicates how it may be determined from the equilibrium volatility or A. S. T. M. distillation data. The fourth paper relates effective volatility to engine performance and suggests the A. S. T. M. distillation characteristics required for satisfactory performance under different conditions of atmospheric temperature. The fifth paper discusses the relation of vapor pressure to vapor lock and suggests the fuel characteristics requisite to insure freedom from this trouble.

THE most important characteristic of a fuel is its ability to start the motor in which it is to be used. Motor-car drivers readily recognize differences in the effect which

[1] The investigations reported in this series of papers have been carried out during the past four years in the Chemical Engineering Laboratory of the University of Michigan. Owing to the interdependence of various phases of the work, publication of the results has been delayed. More complete information than can be given in this series of papers will be found in *Bulletin* **14** of the Department of Engineering Research of the University of Michigan, available in the near future.

[2] Received April 26, 1930.

[3] Part of a thesis submitted by Charles L. Nickolls in partial fulfilment of the requirements for the degree of doctor of philosophy at the University of Michigan.

various fuels have on the ease of starting and frequently judge the value of a fuel almost entirely on this basis. It is extremely important for both consumer and producer to understand what qualities make a fuel effective in starting the motor easily and quickly.

Previous Investigations

During the past six years an extensive investigation of engine starting has been conducted at the Bureau of Standards as part of the coöperative fuel research program. Cragoe and Eisinger (*3*) identify the vaporization of fuel in the carburetor and manifold of a motor during the cranking period as "engine distillation." This engine distillation is not a simple equilibrium distillation, such as was described in Part I of this series (*2*). It does not take place at atmospheric pressure nor necessarily at atmospheric temperature. On account of the choke and throttle, the absolute pressure in the manifold during the cranking period may be considerably less than atmospheric. This would tend to cause more of the fuel to vaporize than would be the case in an equilibrium air distillation. The latent heat of vaporization of the fuel must come either from the surrounding metal part of the carburetor and manifold, from the air, or from the liquid fuel itself. The absorption of this latent heat lowers the temperature of the mixture and tends to decrease the amount of fuel vaporized. Furthermore, the short time interval for the completion of the engine distillation clearly indicates that equilibrium conditions would not be obtained during the cranking period.

On the assumption that the decrease in pressure in the manifold tends to compensate for the decreased temperature due to the latent heat of vaporization and also for the short time interval allowed for engine distillation, the resultant mixture attained in the equilibrium air-distillation may be regarded as the ideal attainable only in infinite time in the engine distillation. Thus the efficiency of the engine distillation may be defined as the ratio of the air-vapor ratio attained in the equilibrium distillation to that attained in the engine distillation. This efficiency depends only slightly upon such factors as temperature, fuel, mixture-ratio supplied, and cranking speed, but does depend almost entirely upon the number of engine revolutions.

Cragoe and Eisinger concluded that about ten revolutions of the engine were required to obtain an explosive mixture in the cylinders when a mixture was supplied at the lower end of the manifold, which would give a resultant air-vapor mixture of 12 to 1 under equilibrium conditions. They derived the following equation which fitted their experimental data with an accuracy of about ±25 per cent:

$$\log R_{EAD} = 1.301 - \frac{2}{N} \qquad (2)$$

Table I—Relation between Engine and A. S. T. M. Temperatures for Starting with a 1:1 Air-Fuel Ratio

Vaporized	Resultant Air-Vapor Ratio	Engine Revolutions to Start	$\frac{T_{ASTM}}{T_{EAD}}$	Engine Temperature							
				30° C. 86° F.	20° C. 68° F.	10° C. 50° F.	0° C. 32° F.	−10° C. 14° F.	−20° C. − 4° F.	−30° C. −22° F.	−40° C. −40° F.
				Corresponding A. S. T. M. Distillation Temperature							
Per cent				° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.
5	20	∞	1.301	252	228	205	181	158	135	111	88
6.5	15.4	20	1.284	240	216	193	171	147	125	102	79
7.5	13.3	13	1.2774	237	214	192	169	145	122	99	77
10	10	7	1.27	232	209	187	164	141	119	95	74
25	4	3	1.284	240	216	193	171	147	125	102	79
Average of last four lines				237	213	191	168	145	122	99	77

where R_{LAD} = resultant air-vapor mixture attained in equilibrium-air distillation
N = number of engine revolutions

This equation corresponds to a 20-to-1 air-vapor mixture required in the cylinders for starting.

Cold-Room Tests

Since these conclusions were based entirely upon tests made over a limited temperature range and with the special set-up described by Eisinger, it seemed desirable to make a thorough investigation of the ease of starting a cold motor with widely different fuels when the motor was driven by the electric starter supplied from the same battery as was used for ignition and with the standard carburetor mounted on the manifold instead of the special fuel system used in the tests at the Bureau of Standards.

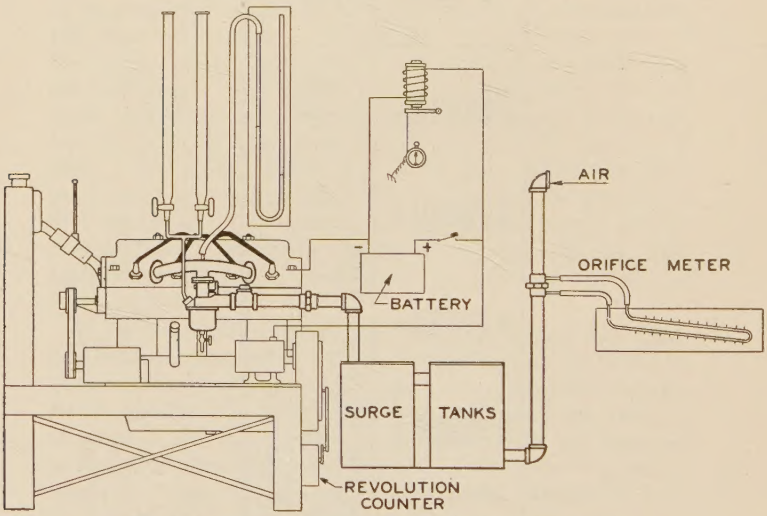

Figure 1—Apparatus Used in Making Starting Tests

Apparatus—The tests reported in this investigation were made on a small, water-cooled, four-cylinder, valve-in-head passenger car motor of $3^{11}/_{16}$-inch bore and 4-inch stroke. (Figure 1) The motor was standard equipped in every way except that the fan blades were removed, and in most tests a battery of larger capacity was used than is ordinarily supplied with this motor. Extensive tests showed that the use of the larger battery had no effect except to give slightly more consistent results and it required less frequent charging.

The starting switch is interconnected with a solenoid, which automatically starts the stop watch as soon as the starter button is depressed and stops it upon release of the starter button. The revolution counter is actuated directly by the motor.

In order to determine the air-fuel ratio supplied by the carburetor, the rate of air-flow is measured by the orifice meter placed before two 5-gallon surge tanks in the air line to the carburetor, and the fuel used recorded as the difference between the readings on the fuel burets before and after the test. Since the revolution counter is direct connected to the motor, the total revolutions of the motor are recorded even if the motor continues to run for a few moments after the starter button and ignition are turned off.

PROCEDURE—In starting a series of tests, the carburetor was carefully wiped dry and the motor cranked for about 100 revolutions with no gasoline in the carburetor to insure that the tests would not be influenced by the fuel previously used. The burets were then filled with the fuel to be tested, and the bowl of the carburetor was lightly tapped to insure proper seating of the float needle valve.

All tests were made at a fixed throttle of about one-quarter open. The stop watch was set to zero and the reading on the revolution counter recorded. Room temperature and barometer readings were also recorded at this time, and in most cases the specific gravity of the fuel was also recorded. The starter button was then depressed, automatically closing the ignition switch and starting the stop watch. The time taken to obtain the first explosion was automatically recorded by the stop watch, and the revolutions of the motor when the first explosion was obtained were read from the revolution counter, at which instant the starter button was also released. The average r. p. m. was obtained by dividing the revolutions required for starting by the fractional part of a minute required to obtain the first explosion.

At the conclusion of such a test the carburetor bowl and burets were drained of fuel as a check on the readings of the burets. The carburetor, after being allowed to drain for 5 or 10 minutes, was carefully wiped dry. The motor was then cranked for about 100 revolutions previously to making the next test.

Each series of tests was started with the choke open to see if a start could be obtained without choking. The following tests were then run at the various fixed choke positions until a perfect start in three or four revolutions was obtained. At least three checks were obtained at each choke setting.

In order to obtain temperatures below that of the laboratory, the motor was placed in a room cooled by direct expansion of ammonia. At the lower temperatures it was found necessary to dilute the oil with at least 25 to 30 per cent of gasoline in order to make cranking possible. Many undiluted special low cold-test oils were tried, but without success. The capacity of the storage battery also approaches zero at about $-40°$ F. and many of the tests were made possible only by bringing a warm battery into the cold room.

RESULTS—As has been frequently reported, starting was found to be far more difficult at low cranking speeds such as

20 r. p. m., than at the higher speeds, such as 140 r. p. m. However, when the air-fuel ratio supplied by the carburetor was computed for these different conditions, it was found that the same number of engine revolutions were required for a given air-fuel ratio at the carburetor regardless of cranking speed.

By dividing the total fuel used by the total engine revolutions, the fuel used per engine revolution is obtained. By dividing the air flow in cubic feet per minute by the average revolutions per minute, the air supplied per revolution is similarly obtained. These data are plotted separately in Figures 2 and 3. It is seen that the points fall on smooth curves which may be used in determining the air-fuel ratio

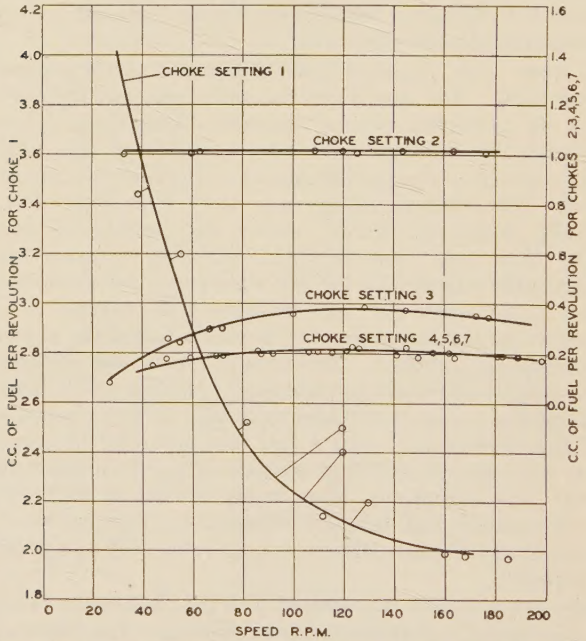

Figure 2—Volume of Fuel Consumed per Revolution of Motor Plotted as a Function of the Cranking Speed for Different Choke Settings

supplied by the carburetor at any of the fixed choke settings and motor r. p. m., provided only the specific gravity of the fuel at the temperature in the buret is known. All the data obtained regarding the number of revolutions required to start could then be plotted as a function of the air-fuel ratio supplied at the carburetor for a given room temperature.

By use of the relationship given by Brown and Skinner (*2*) and the continuous vaporization curves of the fuels used in these starting tests, as given in Figure 4, the resultant air-vapor mixtures formed under equilibrium conditions from the air-fuel ratios supplied at the carburetor were computed. In Figure 5 the log of the resultant air-vapor mixture is plotted

as a function of the reciprocal of the number of revolutions required to start. For purposes of comparison, the straight line deduced by Cragoe and Eisinger is also shown in Figure 5.

The results of this investigation using standard commercial equipment agree within the experimental error with those obtained at the Bureau of Standards using a motor specially equipped and cranked by a dynamometer.

Effect of A. S. T. M. Distillation on Ease of Starting

Although the equilibrium volatility of a fuel cannot be accurately predicted by any simple relationship from the

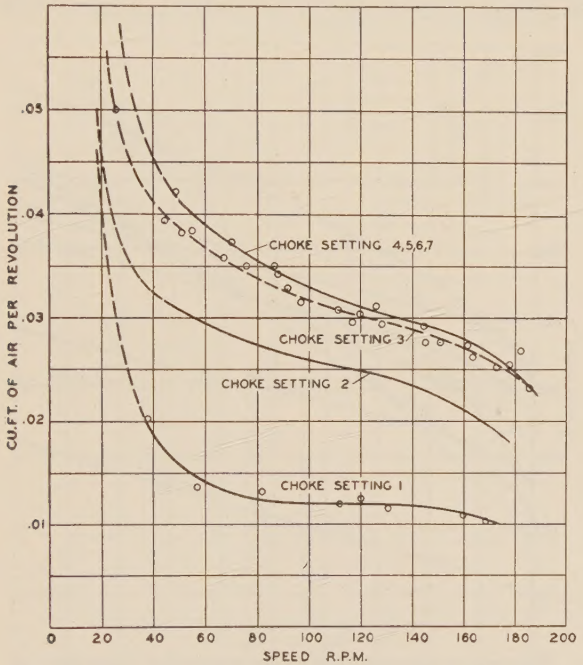

Figure 3—Volume of Air Consumed per Revolution of the Motor Plotted as a Function of the Cranking Speed for Different Choke Settings

lower end of the A. S. T. M. distillation curve, the actual starting tests are consistent only within ±20 per cent, so that any relationship accurate within these limits should prove satisfactory for all practical purposes.

The original relationship given by Cragoe and Eisinger was apparently based on inadequate information, and the results appear optimistic. For example, it was suggested that any fuel having a 5 per cent point on the A. S. T. M. distillation at or below 119° F. should start a car with a 1:1 air-fuel ratio at a temperature of −40° F. Fuels 5115 and 1041 used in the present investigation just about meet this requirement, but it was impossible to start the motor at −26° F. with fuel

5115 in this air-fuel ratio. In fact, it required 30 revolutions to start with this fuel at this temperature with an air-fuel ratio of 0.3:1. Similarly, it was found impossible to start the motor with fuel 1041 at −30° F. even with an air-fuel ratio of 0.3. Just possible starting with fuel 1041 in an air-fuel ratio of 1:1 was found to occur at about −15° or −17° F. Again Cragoe and Eisinger indicated possible starting at 40° F. with a 1:1 air-fuel ratio if the fuel has 5 per cent distilled on the A. S. T. M. distillation at 230° F., but experiment shows that fuel 29 with 5 per cent distilled below 200° F. gives possible starting with a 1:1 air-fuel ratio only at temperatures well above 40° F.

Bridgeman (*1*) has revised these relationships upon the basis

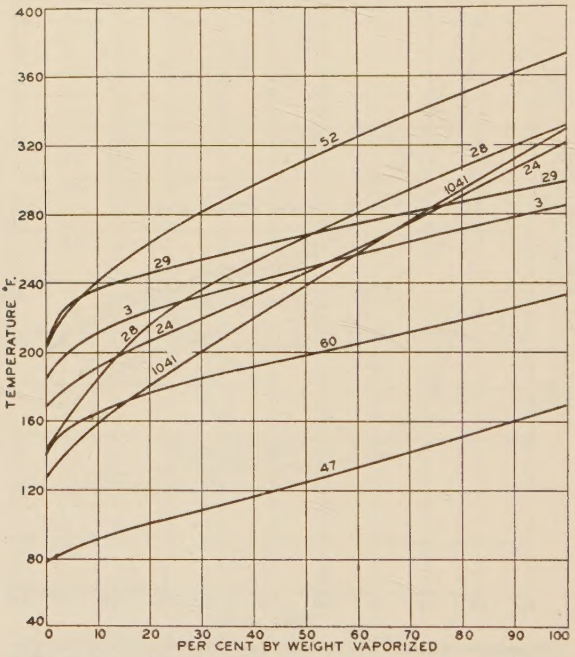

Figure 4—Equilibrium Vaporization Curves of Fuels Used in Starting Tests and in Tests for Effective Volatility

of his first approximation of the equilibrium-air distillation from the A. S. T. M. distillation. The results appear well within the experimental error in determining ease of starting with a 1:1 air-fuel ratio. Computations based on these relationships are given in Table I.

If the resultant air-vapor mixture of 20, requiring approximately an infinite number of revolutions for starting, be disregarded as impractical and only those mixtures which enable the motor to be started in 20 revolutions or less be considered, the A. S. T. M. temperature for 6 to 25 per cent vaporized is practically constant for each engine temperature. If these

temperatures are averaged, as has been done in the table, the average A. S. T. M. temperature may be used with an error of less than ±4° F. to indicate all practical degrees of ease of starting at the corresponding engine temperature.

Similar considerations for other air-fuel ratios indicate a similar constancy of temperature on the A. S. T. M. distillation corresponding to particular engine temperatures. These temperatures are plotted for convenience in Figure 6. For purposes of comparison, actual experimental data obtained with the fuels whose A. S. T. M. distillation curves are shown in Figure 7 are plotted in Figure 6. The lines represent the relation between engine temperature and the corresponding A. S. T. M. temperature for the indicated air-fuel ratios. The

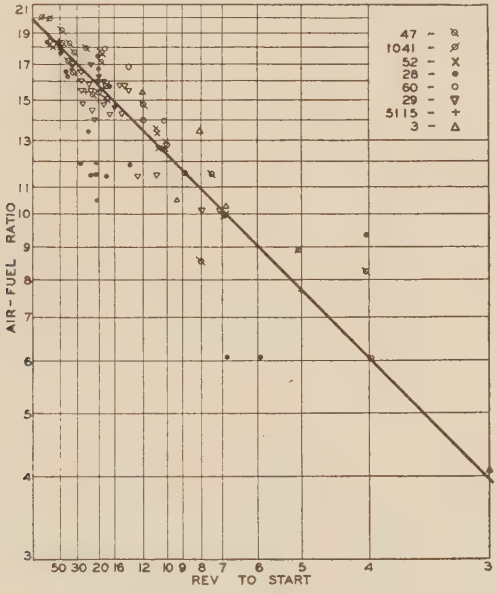

Figure 5—Resultant Air-Vapor Ratio Obtained under Equilibrium Conditions Plotted as a Function of the Revolutions Required to Start

Computed from the data of Figure 4, by the method outlined in the first paper in this series. The solid straight line is that deduced by Cragoe and Eisinger.

percentages tabulated along each line indicate the percentage of fuel that must be vaporized in the A. S. T. M. distillation at the corresponding temperature to insure a start in the indicated number of engine revolutions with the air-fuel ratio specified on the line. For example, at an air-fuel ratio of 1, an engine temperature of 10° F. corresponds to an A. S. T. M. distillation temperature of 140° F. At the given air-fuel ratio, a fuel which is 10 per cent vaporized at 140° F. in the A. S. T. M. distillation will enable the motor to be started in seven revolutions; 6.5 per cent vaporized will enable the

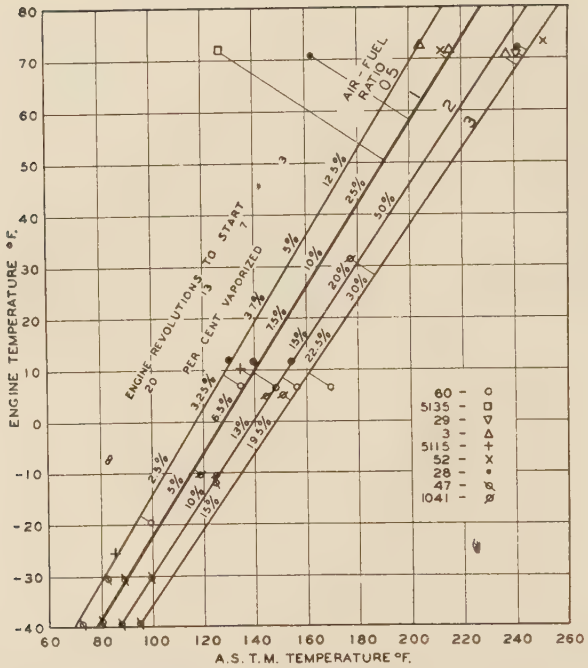

Figure 6—Relationship between Engine Temperature and A. S. T. M. Distillation Temperature for Starting a Cold Motor

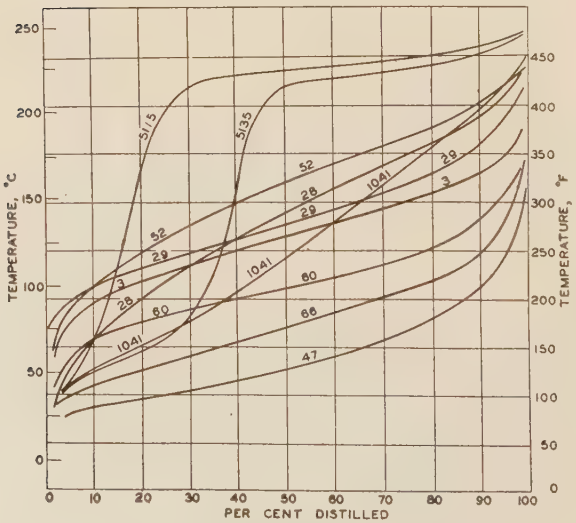

Figure 7—A. S. T. M. Distillation Curves of Fuels Used in Starting Tests

motor to be started in 20 revolutions; while 5 per cent vaporized indicates a possible start in 100 or more revolutions.

Since the A. S. T. M. distillation characteristics of these fuels are known and actual starting tests were made, these data serve as a check of the accuracy of the relationship between the A. S. T. M. and equilibrium-air distillations as well as that of the relationship derived by Cragoe and Eisinger between the resultant air-vapor mixture and the number of revolutions required to start. The agreement between the experimental data and the curves representing this equation seems to be within the experimental error in all cases except two.

In past discussions starting has been regarded as possible if the motor could be made to fire in any number of revolutions up to an infinite number. It is very questionable if it is actually possible to start a motor in cold weather if more than 20 or 30 revolutions are required. By that time the capacity of the battery may have been completely exhausted and what may be regarded as theoretical possible starting becomes an actual impossibility.

At low engine temperatures, oil or battery conditions limit the maximum number of revolutions in which a start must be obtained. With a low-viscosity oil recommended for cold-weather operation the motor could not be cranked at all at a temperature of $-10°$ F. When this oil was diluted 50 per cent, only 19 revolutions could be obtained from a fully charged battery at an engine temperature of $-20°$ F. For these reasons it is clear that possible starting at low temperatures demands a fuel so volatile as to start within 10 or 20 revolutions. At higher temperatures 10 or 20 revolutions may be considered an easy start. Furthermore, the lower cranking speed at the low temperatures causes a more dilute mixture to be supplied by the carburetor, thereby making starting still more difficult.

Proper allowance for this increased difficulty of cranking and starting a motor in cold weather should be made by using fuels of relatively greater volatility at the lower temperatures.

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(1) Bridgeman, *J. Soc. Automotive Eng.*, **22**, 447 (1928).
(2) Brown and Skinner, IND. ENG. CHEM., **22**, 278 (1930).
(3) Cragoe and Eisinger, *Trans. Soc. Automotive Eng.*, **22**, Pt. I, 1 (1927).

IV—Relation between Atmospheric Temperature, Fuel Volatility, and Engine Performance[1,2]

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IN PART III the effective volatility of motor fuels was related to the equilibrium vaporization curve, and used as a means of interpreting the A. S. T. M. distillation directly into terms of engine performance as a function of mixture temperature and air-fuel ratio. These conclusions were based upon tests made on one motor equipped with a special carburetor. It would seem, however, that unless the efficiency with which the liquid fuel is distributed differs radically for different types of manifolds these conclusions might be applicable to most commercial motor cars if the mixture temperatures for different driving conditions were known.

The mixture temperatures under actual driving conditions have been determined in a series of road tests covering about three years and atmospheric temperatures ranging from −20° to 90° F. The conclusions presented in Part III have been found applicable to other commercial motors and initial speeds by a series of acceleration tests under carefully controlled conditions in the laboratory. By combining these data obtained with commercial equipment it is possible to suggest distillation characteristics of motor fuels that will insure satisfactory car performance under any ordinary condition of use.

ROAD TESTS

The road tests were made with different vehicles in which the mixture temperatures measured in the same manner as reported in the previous paper were taken under different driving conditions. These temperatures, as was to be expected, varied within rather wide limits for different conditions with the same car. But much greater differences in mixture temperatures were noted between different cars even under similar driving conditions. This was particularly noticeable in cold weather, when those cars equipped with radiator shutters generally operated at much higher mixture temperatures than those not so equipped.

After the motor had become warmed up to a fairly steady state, fluctuation in the mixture temperature seldom exceeded 40° F. on cars not equipped with radiator shutters and usually remained constant within about 15° F. in the case of those

[1] Received April 26, 1930. Presented before the Division of Petroleum Chemistry at the 79th Meeting of the American Chemical Society, Atlanta, Ga., April 7 to 11, 1930.

[2] Part of a thesis submitted by Charles L. Nickolls in partial fulfilment of the requirements for the degree of doctor of philosophy at the University of Michigan.

cars equipped with automatic radiator shutters. On the other hand, variations as great as 60° to 80° F. were frequently observed between different cars under the same driving conditions. In all cases the mixture temperature rose rapidly when speed was slackened after the car had been driven hard for more than 5 minutes, but returned rapidly to the steady state in 1 or 2 minutes. The reverse is also true. The mixture temperature dropped for about 1 minute whenever the car was accelerated.

In most cars not equipped with radiator shutters the mixture temperature, even when the steady state is reached, appears to be directly proportional to the atmospheric tem-

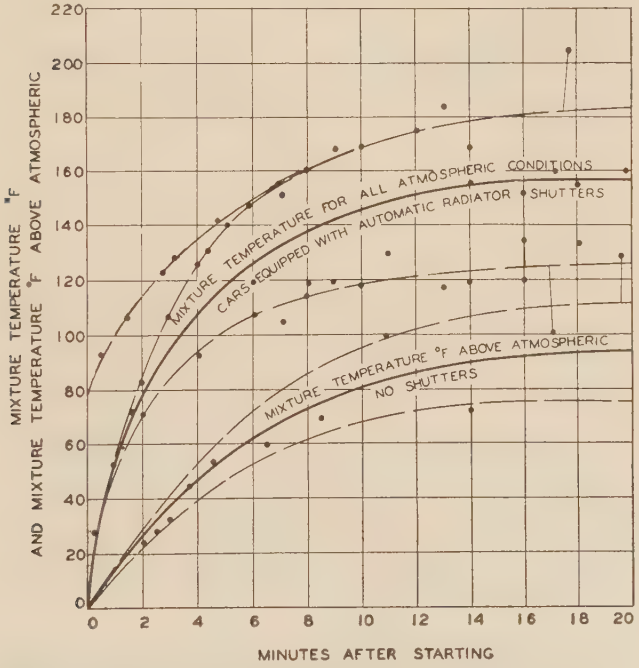

Figure 1—Mixture Temperature Plotted as a Function of Time after Starting

Lower series of curves for cars not equipped with automatic radiator shutters and tending to have low mixture temperatures.
Upper series of curves for cars equipped with automatic radiator shutters and effective manifold hot box.

perature. For this reason the difference between the mixture temperature and the outside or atmospheric temperature is plotted in Figure 1 as a function of the time after the cold motor is started, for cars not equipped with shutters. On the other hand, cars with radiator shutters tend to operate under approximately constant mixture temperatures after the warming-up period. For this reason the curves for these cars represent actual mixture temperature in Figure 1.

Because of the practical importance of determining the

mixture temperature entering the cylinder block on different cars in order to estimate the A. S. T. M. characteristics required to give satisfactory performance under different conditions, the data reported by Mock (*2*) are valuable as a means of checking the data obtained in the present investigation.

With an atmospheric temperature of 40° F. and a car not equipped with shutters a mixture temperature of 80° F. is indicated in Figure 1 as observed in the manifold near the point at which the mixture enters the cylinder block during the warming-up period (about 3 to 4 minutes after starting). For similar conditions with the air entering the carburetor at 40° F., Mock reports:

> Approximately 8 per cent of the fuel will evaporate at the jet and the remainder will strike the heating walls; if the exhaust temperature be 900° F., the wall temperature will be perhaps 120° F. and the fuel will flow along it at slightly below this temperature evaporating at its surface as the air stream scrubs it. The final mixture will be low in temperature (80° F.) and decidedly wet.

The mixture temperature indicated in Figure 1, after the motor had become warmed to its steady state, varies generally between about 120° and 150° F. In discussing steady conditions on a spring day, Mock reports:

> With air and fuel entering the carburetor at 100° F., 40 per cent of the fuel may evaporate in the carburetor, and the remainder may cool the hot spot wall to about 380° F.; the liquid fuel on the walls will be much less in quantity than before and probably it will evaporate before leaving the manifold reaching the cylinders as a thin fog at a temperature between 130° and 150° F.
>
> Finally, assume entering air and fuel temperatures of 150° F., which I have actually observed on a hot summer day. Under these conditions the fuel has probably disappeared into vapor 6 inches beyond the jet, and no liquid is on the hot-spot walls, the temperature of which may now rise above 600° F., hot enough to discolor brass and to char any but asbestos gaskets. The radiation effect from the walls will be considerable at this temperature, and the mixture temperature at the cylinder port may reach 200° F.

In road tests on an 8-cylinder, L-head, water-cooled motor equipped with thermostatically controlled radiator shutters and with the carburetor located in the center of the V between the exhaust manifolds, the air entering the carburetor generally exceeds 150° F., even with an outside temperature considerably below 0° F. In warm weather air entering the carburetor on such cars may frequently exceed 200° F. Under such conditions mixture temperatures of 200° F. or more are frequently observed, particularly when speed is slackened, or when a high speed, as of 65 miles per hour, has been maintained for about 10 minutes.

Under some conditions, as after a period of hard driving, considerably higher temperatures have been observed. Mock reports mixture temperatures as high as 320° F. a few moments after speed was reduced from a steady high-speed, cross-country run during which the mixture temperature

averaged about 150° F. with air passing into the carburetor at 110° F.

Extensive tests on different motors indicate that the relationships between mixture temperature and atmospheric temperature given in Figure 1 are generally representative of the two classes of motor cars now in common use—those equipped with radiator shutters, which operate at reasonably constant temperatures when thoroughly warmed to the steady state, and those cars not equipped with radiator shutters and consequently influenced to a much greater degree by atmospheric conditions.

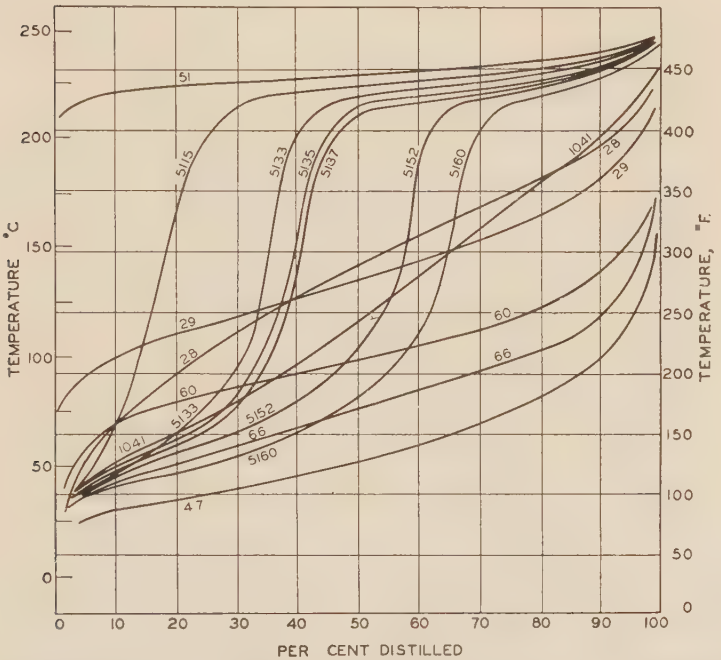

Figure 2—A. S. T. M. Distillation Curves of Fuels Used in Determining Relationship between A. S. T. M. Distillation Characteristics and Acceleration Performance

Preliminary road tests with fuels such as those shown in Figure 2 indicated that the relationship between the A. S. T. M. distillation, effective volatility, and engine performance, as given in Figure 16 of Part III is sufficiently general to be applicable to all types of motor cars provided the mixture temperature is known within 5° or 10° F. Since this range in temperature is within the limits with which the mixture temperature can be estimated from Figure 1, the relations indicated seem sufficiently accurate for all practical purposes.

LABORATORY TESTS

Road tests are notoriously unsatisfactory and unreliable in

drawing such conclusions because of the many variables impossible to control in a satisfactory manner. For this reason all data obtained by road tests, except those concerning the mixture and jacket temperatures obtained under representative driving conditions, were entirely discounted and a series of laboratory tests was made with different types of motors, factory-equipped and adjusted except where otherwise noted. In these tests the motors were operated under temperature conditions similar to those found when the same type of motor was used to drive the car for which it was designed.

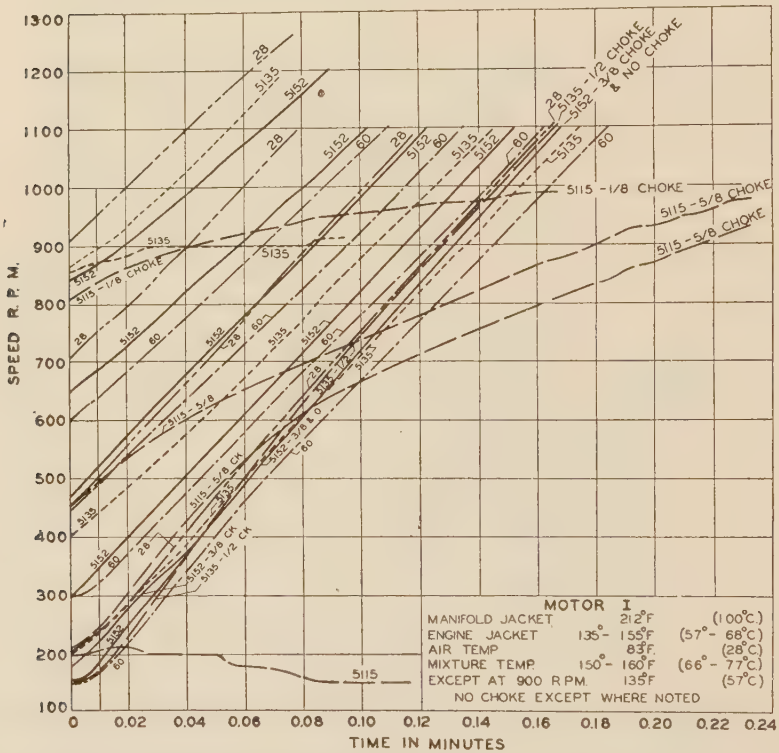

Figure 3—Acceleration Curves Obtained with Motor I, Factory Adjustment, Operated under Conditions Indicated

Motor I—Factory Adjustment

Since the effective volatilities reported in Part III were determined entirely from an initial speed of 300 r. p. m. and with special carburetor equipment, the first tests were run in the same manner as those described in Part III on the same 6-cylinder, valve-in-head, watercooled motor, Motor I, but with the standard factory carburetor as shown in cross section in Figure 1 of Part III and starting from initial speeds ranging from 150 to 900 r. p. m. This carburetor does not supply a constant air-fuel ratio throughout the period of an accelera-

tion. Owing to the combined action of an auxiliary gasoline valve, which is opened and closed with the throttle, and the spring loaded air valve, a richer mixture is supplied when the throttle is opened, particularly at the lower speeds. For this reason the effective volatilities cannot be determined directly from the acceleration made with the standard carburetor, but the conclusions based on the effective volatilities as stated above can be tested by direct comparison with the accelerations shown in these tests.

Warm Motor, Warm Manifold—The acceleration curves

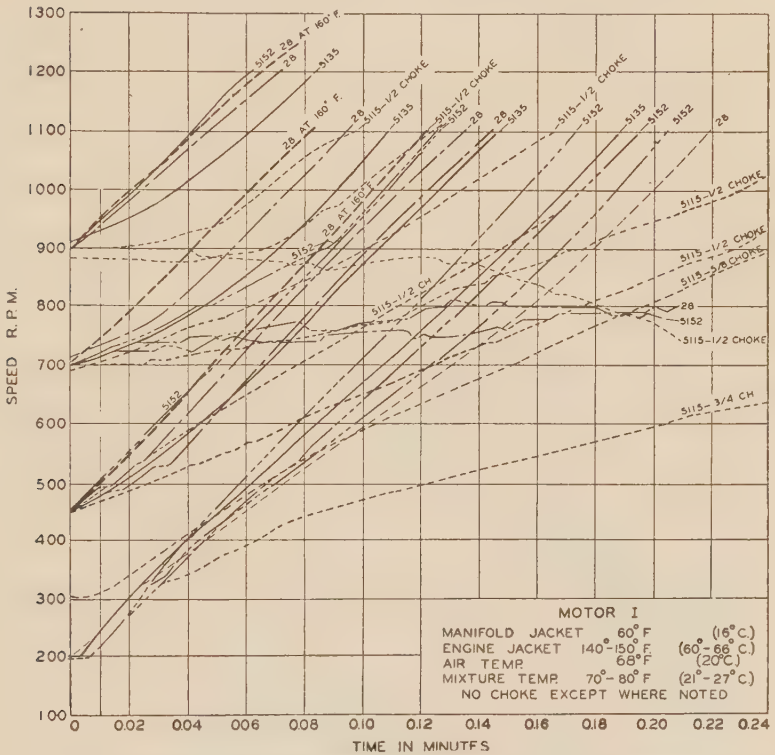

Figure 4—Acceleration Curves Obtained with Motor I, Factory Adjustment, with the Motor Warm but Manifold Cool

obtained with the warm motor and with the manifold jacket heated with steam, representative of normal warm weather driving conditions, are shown in Figure 3. Fuel 28 is a representative motor fuel, and may be used as a standard of comparison. Except at extremely low speeds, it shows the best acceleration of any of the fuels tested in this series.

Beginning at a speed of 150 r. p. m. fuel 5152 shows a better accelerating curve than fuel 28 starting at 200 r. p. m. Since this inferiority of fuel 28 is not observed in those accelerations beginning at speeds greater than 400 r. p. m., it must be due

to some difference in mixture conditions caused by the different initial speed. With this carburetor a rich mixture of about 10 : 1 air-fuel ratio is supplied at idling speeds and the air valve opens more slowly than when the test is started from higher speeds. Furthermore, at the higher speeds the effect of any accelerating charge is noticeable only over a much shorter period of time and to a lesser degree because of the greater air and fuel consumption. Since fuel 28 is at least 70 per cent effectively vaporized at this mixture temperature, the best acceleration will be obtained with a mixture ratio not much richer than 10 : 1. This demands little or no en-

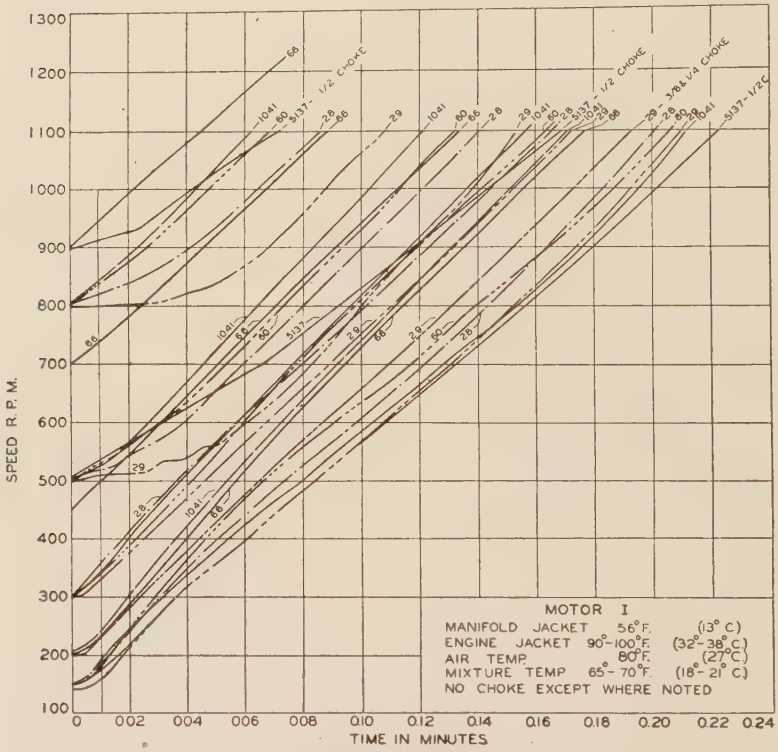

Figure 5—Acceleration Curves Obtained with Motor I, Factory Adjustment, with a Cool Motor and Cool Manifold Jacket

richment of the mixture, or only a very limited accelerating charge at the lower speeds. For these reasons the loss in power brought about by mixture enrichment in the case of fuel 28 causes the acceleration produced with this fuel at an initial speed of 200 r. p. m. to be less than that of fuel 5152. After the over-rich mixture supplied during the first 2 or 3 seconds has been consumed, the acceleration produced by fuel 28 is equal to that of fuel 5152.

This is probably the true explanation for the poorer performance frequently observed when using fuels of low 90

per cent A. S. T. M. points on modern motors equipped with heated manifolds. In discussing a series of long-time road tests on motor coaches, Hughes (*1*) reports:

> They are equipped with six-cylinder engines of 77 maximum boiler horsepower and the conventional vented cooling system. Certain strength gasolines produced a fair mileage per gallon but failed to give the necessary maximum power when required. These gasolines were found to have relatively equivalent initial boiling and 50 per cent points in comparison with other more satisfactory gasolines, but their end points werein the neighborhood of 395° to 400° F., whereas those of a higher end point, around 415° to 425° F., gave ample power under all conditions.
>
> The four-cylinder engines develop 54 maximum boiler horsepower and are equipped with the Foutz cooling system. This is a

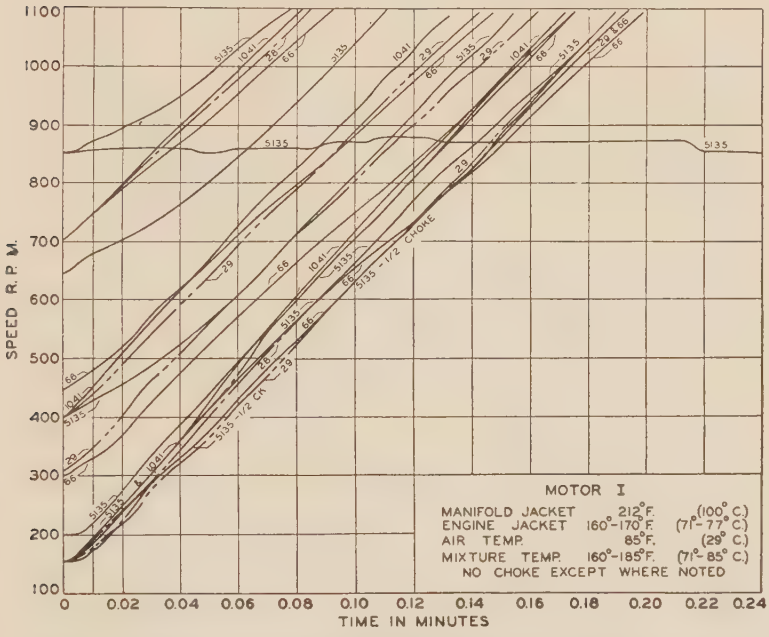

Figure 6—Acceleration Curves Obtained with Motor I, Factory Adjustment, with a Warm Motor and Warm Manifold

closed water-cooling system which heats up quickly and operates at temperatures considerably higher than those of the conventional system and which are uniform under varying external conditions. Here, again, the high-end-point gasolines have developed appreciably more power and show no effect on dilution.

The loss in acceleration due to a low 90 per cent point is even more pronounced in the case of fuel 60, which is completely vaporized at all mixture temperatures above 130° F. At an initial speed of 450 r. p. m. fuel 60 shows a noticeably poorer acceleration throughout the entire curve than fuel 28 and, with the single exception of fuel 5115, the poorest acceleration from an initial speed of 150 r. p. m. of any of the fuels tested in this series.

Comparison of the curves shown in Figure 3 clearly indicates that under these conditions fuel 60 no in case gives better acceleration than fuel 28 or 5152, and at low speed is considerably inferior to these fuels of much higher end point.

The fact that fuel 5152 gives satisfactory acceleration in all cases without use of the choke, and no improvement in acceleration when the choke is used, clearly demonstrates that under these conditions that part of the A. S. T. M. distillation above 60 or 65 per cent has little or no effect on the acceleration in so far as providing effective volatility is concerned. At the higher initial speeds, as above 600 r. p. m., when the mixture enrichment due to accelerating devices has much less effect, the acceleration produced

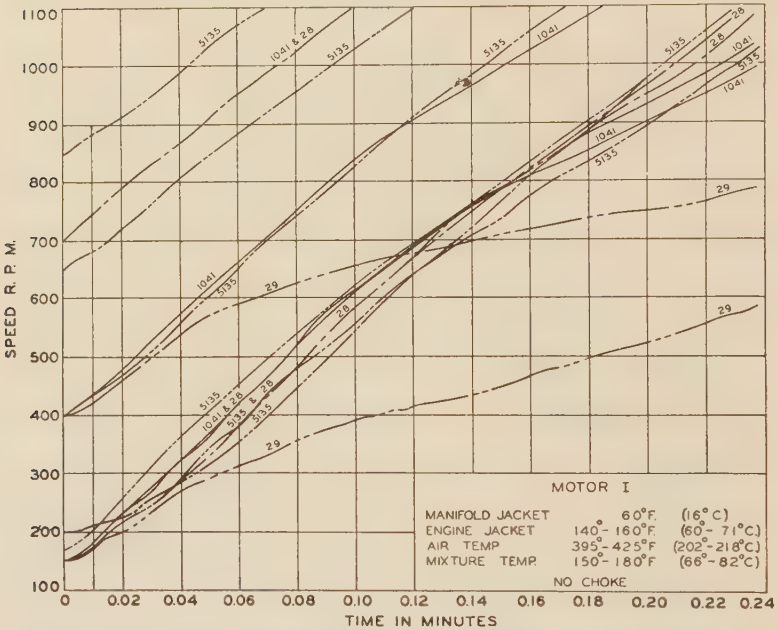

Figure 7—Acceleration Curves Obtained with Motor I with a Cool Manifold but with Air Heated to About 400° F.

by fuel 5152 is not quite equal to that of fuel 28 but is still considered satisfactory. At an initial speed of 450 r. p. m. a direct comparison may be made between fuels 28, 5152, and 60. Fuel 28 gives the best acceleration with fuel 5152 only slightly inferior, but fuel 60 gives the poorest of the three.

When the choke is used, fuel 5135 gives an acceleration equal to that of any of the fuels tested and superior to that of fuel 28 or 60. As indicated in Figure 16 of Part III, fuel 5135, having its 35 per cent point on the A. S. T. M. distillation below 250° F., should possess about 45 per cent effective volatility in a 6 : 1 fuel ratio at any mixture temperature above

110° F. At these low initial speeds the combined action of the accelerating devices in this carburetor has its maximum effect and if the mixture enrichment without choking is equivalent to delivering an air-fuel ratio of about 6 : 1 at the carburetor, an air-fuel ratio of about 14 : 1 would be supplied to the cylinders during the accelerating period. The acceleration curves in Figure 3 indicate that this conclusion is substantially correct. At an initial speed of 850 r. p. m. less enrichment of the mixture is accomplished and fuel 5135 appears to have such volatility as to be on the border line between that giving entirely satisfactory and unsatisfactory performance without use of the choke. Clearly, at least 35 per cent must be vaporized to insure satisfactory performance.

A more severe test of these relations is that provided by fuel 5115, having a low 10 per cent point but an 18 per cent point of about 280° F., indicating that probably about 15 per cent of this fuel is actually vaporized under the test conditions. At an initial speed of 800 r. p. m. the choke was pulled out one-eighth, which was the minimum amount necessary to keep the motor running. At the lower speeds of 450 and 200 r. p. m. the choke was pulled out five-eighths and somewhat better performance was obtained. In fact, for the first 0.05 minute the acceleration with fuel 5115 from an initial speed of 200 r. p. m. was the equal of any of the fuels tested. When the choke was not used at an initial speed of 200, no acceleration could be obtained.

Warm Motor, Cool Manifold—A similar series of tests was run on the same motor with the same engine-jacket temperature but with the mixture temperature reduced to between 70° and 80° F. The acceleration curves for this series of tests are shown in Figure 4. The mixture temperature of 70° to 80° F. closely corresponds to the warming-up period on most modern cars at an atmospheric temperature of about 30° F. From Figure 16 of Part III it is seen that, at a mixture temperature of 70° to 80° F., perfect performance without use of the choke is predicted only for those fuels which show 65 per cent or more over on the A. S. T. M. distillation at 120° F. or 45 per cent or more over at 150° F., if a mixture ratio equivalent to 6:1 is supplied at low speeds. Since none of the fuels tested in this series meets either or both of these specifications, perfect performance is not to be expected, but entirely satisfactory performance is estimated for all fuels having 35 per cent or more vaporized at 220° F. Of the fuels under consideration only 60 and 5152 have well over 35 per cent vaporized at this temperature. Fuel 5152 shows 50 per cent vaporized at 220° F. and should give almost perfect performance under the conditions indicated in Figure 4. Fuels 5135 and 28 have about 35 per cent vaporized at 250° F. and should give approximately the same performance under these conditions of test, unless the extremely large percentage of heavy ends contained in fuel 5135 cannot be burned as effi-

ciently as the liquid residue distributed to the cylinders when using fuel 28.

In general these are the results found. With the single exception of the tests started at 700 r. p. m., fuel 5152 shows the best acceleration of any of those tested. The acceleration is almost equal to the best obtained even when the motor was thoroughly warm. It was for the purpose of comparing the fuels under these different mixture temperatures that the engine jacket was maintained at practically the same temperature so that the engine friction would remain constant for the tests indicated in Figures 3 and 4.

The poor accelerations shown from 700 r. p. m. in the case of fuel 5152 are due to the fact that during the first test at this

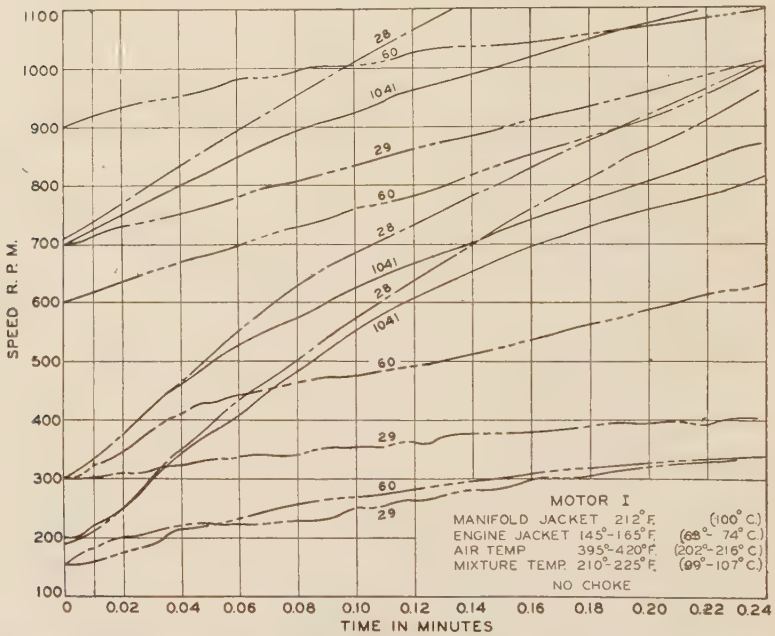

Figure 8—Acceleration Curves Obtained with Motor I with a Heated Manifold and Heated Air, So that Mixture Temperature Is in Excess of 210° F.

speed the fuel supply to the carburetor became exhausted. This caused the motor conditions to change for the next two tests and resulted in the relatively poor accelerations shown for fuel 5152 at an initial speed of 700 r. p. m. The better of the two curves was run with a mixture temperature of 55° F., which indicates the extent to which motor conditions were changed by this disturbance in the procedure. Fuel 28 run in this period also shows practically no acceleration. In view of the results obtained at 200, 450, and 900 r. p. m., the poor accelerations shown for fuel 5152 beginning at 700 r. p. m. should be neglected except as an indication of the sensitivity of the acceleration tests to relatively small changes in mixture temperature.

Apparently 50 per cent vaporized on the A. S. T. M. distillation at 220° F. as represented by fuel 5152 is almost sufficient to insure entirely satisfactory acceleration with mixture temperatures of 70° to 80° F., and 35 per cent vaporized at 220° F., as represented by fuel 5135, is sufficient to give reasonably satisfactory performance under these mixture conditions.

The interpretation of effective volatility as shown in Figure 16 of Part III indicates that a fuel having 10 per cent vaporized at 220° F. should possess sufficient volatility for possible driv-

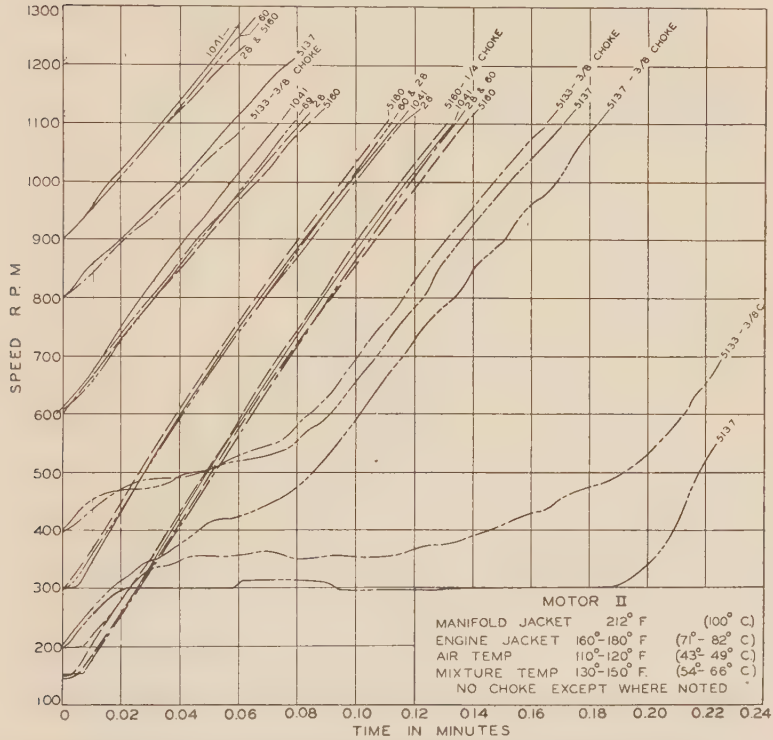

Figure 9—Acceleration Curves Obtained with Motor II, Factory Adjustment, with a Warm Manifold and Warm Motor

ing with the choke when the mixture temperature is between 70° and 80° F. For this reason fuel 5115 was tested with different choke settings, as indicated in Figure 4. The performance is by no means satisfactory, but the results substantiate the conclusion regarding possible performance with use of the choke as indicated by the 10 per cent point on the A. S. T. M. distillation.

Those fuels numbered over 5000 cannot be considered typical motor fuels. They were used as a severe test of the conclusions regarding the importance of partial effective volatility, as indicated by the first half of the

A. S. T. M. distillation. Furthermore, they possess the interesting characteristic of having practically constant volatility between the temperature limits of 200° and 400° F. on the A. S. T. M. distillation, or between the limits of 60° and 200° F. mixture temperature. The tests reported in Figures 3 and 4, in which these fuels show practically the same performance, establish the substantial constancy of their partial volatilities between mixture temperature limits of 60° and 160° F.

These two series of tests serve to extend the interpretation of effective volatility as determined at 300 r. p. m. in terms of A. S. T. M. distillation characteristics and motor performance

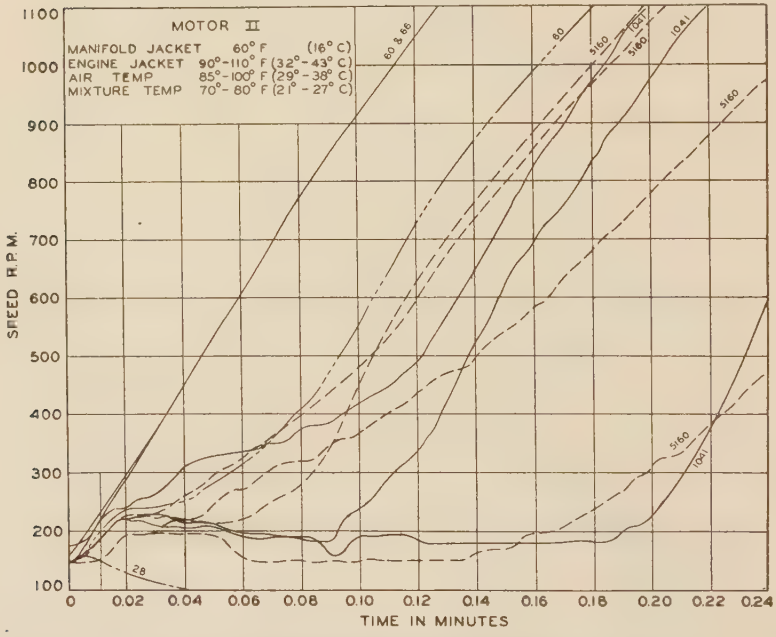

Figure 10—Acceleration Curves Obtained with Motor II, Factory Adjustment, with a Cool Manifold and Cool Motor

over the initial speed range from 150 to 1000 r. p. m. on this particular motor.

Cool Motor, Cool Manifold—Another series of tests conducted with approximately the same manifold-jacket temperature, but with the engine jacket operated at lower temperatures in order to conform more closely with actual driving conditions, is given in Figure 5.

Because of the difference in engine-jacket temperature, it seemed advisable to run fuel 66, which has 70 per cent vaporized in the A. S. T. M. distillation at 200° F. and gives practically perfect acceleration under these conditions, as a standard of comparison. The standards used in Figures 3 and 4 are not applicable to these conditions because of different engine-jacket temperatures.

Fuels 60, 1041, and 5137 offer an opportunity to compare the importance of the 35 per cent point. For a mixture temperature of between 65° and 70° F. it is estimated from Figure 16 of Part III that satisfactory performance can be obtained if the 35 per cent point on the A. S. T. M. distillation does not exceed 200° F. All of these three fuels more than meet this requirement, except 5137, which shows 34 per cent vaporized at this temperature.

Except at initial speeds of about 150 r. p. m. fuel 1041 gives a performance slightly superior to that of fuel 60 and it has a slightly lower 35 per cent point.

Fuel 5137 contains about 60 per cent of material boiling above 425° F. In these tests it was found impossible to ob-

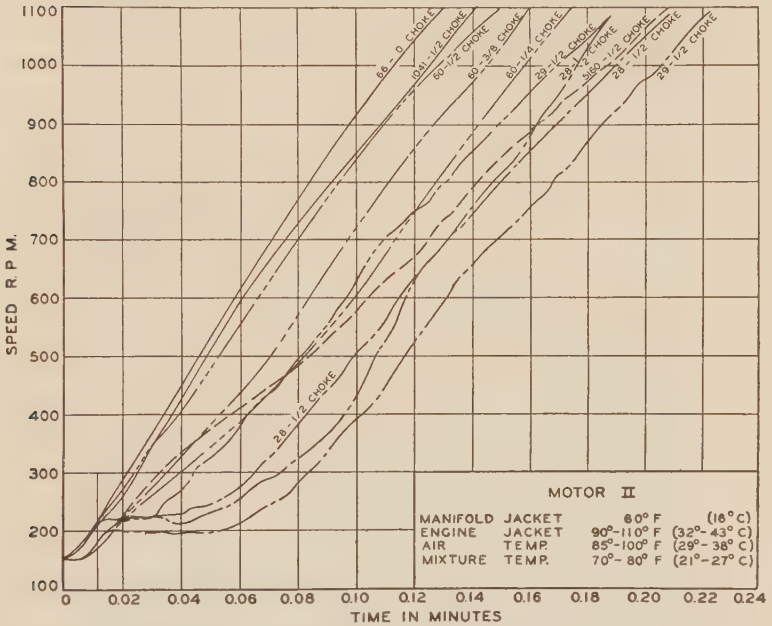

Figure 11—Acceleration Curves Obtained with Motor II, Factory Adjustment, with a Cool Motor and Cool Manifold. Choke Used as Indicated

tain satisfactory acceleration from this fuel unless the choke was used. This is due to the large amount of material in this fuel which is not volatile at these lower engine temperatures and could not be burned efficiently in the cylinders even though a sufficient quantity of the fuel was properly distributed; however, when the choke was pulled out about half way, fairly satisfactory acceleration was obtained. Considering the freakish characteristics of fuel 5137, which just fails to meet the 35 per cent requirement, these results indicate the importance and sufficiency of the 35 per cent point on the A. S. T. M. distillation in determining satisfactory performance during the warming-up period when use of the choke is almost universal.

As a further check on the relative importance of the first

third of the A. S. T. M. distillation against the last two-thirds, comparison may be made of fuels 28 and 29, crossing at about 38 per cent in Figure 2. In all cases fuel 28 is superior to fuel 29 during the warming-up period, as represented by the tests in Figure 5.

The fact that fuels 5135 and 5152 proved satisfactory at the higher engine temperature while fuel 5137 proved unsatisfactory with the lower block temperatures indicates that a 90 per cent point of 450° F., at least when accompanied with a 50 per cent point of over 400° F., is too high for the warming-up period, although it may prove satisfactory from an acceleration standpoint on motors driven in warm weather or in fairly continuous operation. The fact that fuel 1041 with a 90 per cent point of 400° F. proved entirely satisfactory at the lower block temperature, giving better acceleration than the aviation fuel 60, clearly indicates that under these conditions 90 per cent points below 400° F. offer no practical advantage from the standpoint of acceleration or motor performance.

At an initial speed of 200 r. p. m. the acceleration of fuel 1041 is superior to that of fuel 66. This further indicates no practical advantage in the use of fuels of low 90 per cent point on modern automotive equipment, but rather a possible loss in acceleration. In the case of warm motors, as indicated by fuel 28 in Figure 3, 90 per cent points below 400° F. may be the cause of poorer acceleration, when used on modern cars equipped with heated manifolds and effective accelerating devices.

Warm Motor, Warm Manifold—In order to test these conclusions further another series of tests, as indicated in Figure 6, was run in which fuel 1041 could be compared directly with fuels 28, 29, 66, and 5135 on a warm motor.

Comparison of the two series of tests shown in Figures 5 and 6 indicates that a fuel, such as 1041, whose A. S. T. M. distillation curve tends to be concave upward with a low 35 per cent point and low 65 per cent point, but whose 90 per cent point is not under 390° or 400° F., gives the best general performance of modern motors both during the warming-up period and after the motor is warmed to the steady state.

Heated Air—In order to determine if heat supplied to the mixture in the form of heated air instead of through the walls of the manifold had any noticeable effect tending to modify these conclusions, the tests indicated in Figure 7 were run with approximately the same engine-jacket and mixture temperature as those in Figure 3, but with the heat to the mixture supplied entirely through heated air.

Under these conditions the acceleration is reduced in the case of all fuels. This is due largely to the loss in volumetric efficiency caused by the hot air and the resistance of the electric air heater, but is of no moment in the present discussion, which is concerned entirely with the relative perform-

ance of the different fuels. The carburetor was adjusted for this series to deliver the same air-fuel ratio (about 12.3) as in the previous tests.

The results are generally similar to those obtained with cool air except that the loss in acceleration is more clearly evident in the case of the low-end-point fuel 29. This fact seems to indicate again a decided loss in acceleration when fuels having 90 per cent points below 390° F. are used in modern engines. It also clearly indicates that 90 per cent points as high as 450° F. may be used with satisfactory results at least under these conditions.

In order to see what the results would be when the mixture temperature was raised to above 200° F., the manifold jacket was operated at 212° F. with the air heated to over 400° F. Under these conditions the mixture temperature ranged from about 210° to 225° F. and gave the accelerations indicated in Figure 8. In this case the further decrease in acceleration should be attributed, not to friction losses in the air line, which are the same as for the tests plotted in Figure 7, but to the high mixture temperature. The extremely poor acceleration obtained with fuels 29 and 60 as compared with fuels 28 and 1041 is evident. The fact that the acceleration is much poorer with the low 90 per cent point fuels at lower speeds than at the higher speeds is again evidence of the greater effectiveness of the accelerating device at the lower speeds. The poor acceleration of fuel 1041 compared with that of fuel 28 is due definitely to partial vaporization of fuel 1041 in the jet of the carburetor, which causes a lean mixture of this fuel to be supplied to the manifold. During the first few seconds of the acceleration the effect of this lean mixture is overcome by the countereffect of the accelerating device in the carburetor, particularly at the lower speeds. This impoverishment of the mixture as the temperature of the carburetor increases due to vaporization of the fuel is known as "vapor lock." It was evidenced to a much less degree in the test reported in Figure 7, but became more pronounced under the combined influence of hot air and the steam-heated manifold. The subject of vapor lock will be treated in Part V.

In consideration of the fact that the mixture temperatures of 210° to 225° F., as obtained in the test reported in Figure 8, are frequently attained under steady driving conditions on many cars, and often exceeded when the speed is suddenly reduced after a period of hard driving, the advantage in having the 90 per cent point sufficiently high to avoid this loss in acceleration and power at least compensates for the supposed disadvantage of the slight increase in dilution of the oil in the crankcase. The latter has been frequently called to the writers' attention, but the former has not heretofore been generally recognized.

These tests on Motor I serve to extend the effective volatility as indicated in Figure 16 of Part III to other initial speeds, but indicate nothing as to the accuracy with which

these conclusions may be extended to other types of engines, manifolds, and carburetors.

Motor II—Factory Adjustment

For this reason the tests shown in Figures 9 to 12 were conducted on an entirely different type of motor, a 6-cylinder, L-head, water-cooled motor equipped with a ram's-horn type of manifold and a plain-tube, double-jet carburetor. The tests were conducted with all adjustments as made at the factory and with the same dynamometer and inertia disk as used with Motor I. Although the moment of inertia was not quite equal to that of the car which this motor was designed to drive, the difference was slight and the results are comparable to those obtained on the road test with the car. The mixture temperature was taken in exactly the same manner as in the road tests on the same motor plotted as the lower curves in Figure 1, so that the results might be translated directly into motor-car performance at various atmospheric temperatures.

Warm Motor, Warm Manifold—Fuels 5137 and 5133 were compared in an effort to test the sharpness of the 35 per cent point as dividing fuels into those giving satisfactory and unsatisfactory performance. The comparison of the two fuels at an initial speed of 800 r. p. m. in Figure 9 clearly indicates that fuel 5137 gives satisfactory acceleration without use of the choke but that fuel 5133 will not give satisfactory acceleration unless the choke is used. At an initial speed of 400 r. p. m., fuel 5133 choked about three-eighths gave a fairly satisfactory acceleration almost identical to that of fuel 5137 without the choke. A similar comparison was made at an initial speed of 200 r. p. m. In this case fuel 5137 did not give satisfactory acceleration without the choke, as the carburetor did not adequately enrich the mixture at low speeds. When choked three-eighths fairly satisfactory results were obtained with this fuel.

Considerations of effective volatility determined with Motor I as interpreted in Figure 16 of Part III suggest that not less than 35 per cent distilled in the A. S. T. M. distillation at 280° F. is required to give fairly satisfactory performance for a mixture temperature of 130° F. In Motor II, fuel 5137, showing 40 per cent distilled at 280° F., gives satisfactory performance at 800 r. p. m., and fairly satisfactory performance at 400 r. p. m. and at 200 r. p. m. if choked about three-eighths. But fuel 5133, showing 34 per cent distilled at 280° F., gives satisfactory performance only if choked even at the higher speeds. An increase from 34 to 40 per cent vaporized at this temperature makes it possible to obtain the same performance without use of choke as is obtained with three-eighths choke.

It is clear from these tests that at least 35 per cent must be vaporized in the A. S. T. M. distillation at the indicated tem-

perature (Figure 16 of Part III) to insure reasonably satisfactory performance with Motor II. The fact that Motor I gave entirely satisfactory performance at low speeds and only fairly satisfactory performance at moderately high speeds while the opposite is true in Motor II is due, not to fuel characteristics, but to differences in the metering characteristics of the carburetors.

Fuels 5160 and 1041 cross at about 300° F. and 65 per cent on the A. S. T. M. distillation. At the mixture temperatures (130° to 150° F.) existing in this series of tests, 65 per cent distilled at 300° to 330° F. is suggested as the minimum vola-

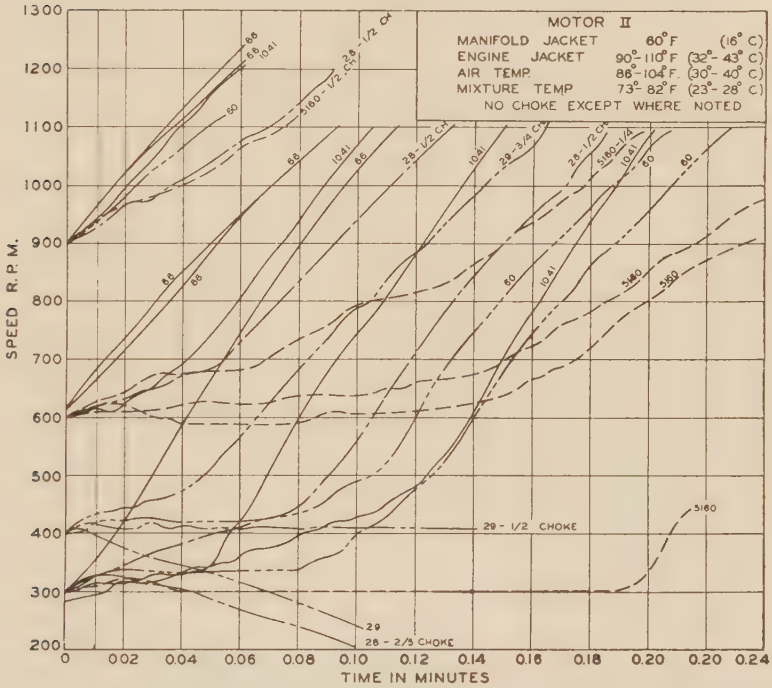

Figure 12—Acceleration Curves Obtained with Motor II, Factory Adjustment, with a Cool Motor and Cool Manifold

tility required to give perfect performance without use of the choke. This is borne out in practice by the almost perfect accelerations of fuels 1041, 28, and 5160 at all initial speeds and the failure of fuel 5137 to produce satisfactory performance except at high initial speeds. By these comparisons it seems that the results obtained in Motor I can be applied directly to Motor II for the same mixture temperature if due account is taken of the air-fuel ratio supplied by the carburetor.

Cool Jacket, Cool Manifold—The conditions given in Figure 9 correspond to a thoroughly warm motor operating at an atmospheric temperature of about 70° F. In order to make

a similar test of the conclusions at a lower temperature, the data plotted in Figures 10, 11, and 12 were taken under conditions representative of the warming-up period in an atmospheric temperature of about 30° F., corresponding to conditions about 1 to 2 minutes after the cold motor is started, as given in Figure 1. According to Figure 16 of Part III, entirely satisfactory performance is to be expected with a mixture temperature of 70° to 80° F. if more than 55 per cent is distilled in the A. S. T. M. distillation at 170° F. Fuel 66 meets this requirement and gives practically perfect performance at all speeds under these conditions. Fairly satisfactory performance is indicated in Figures 11 and 12 at 990 r. p. m. with fuels

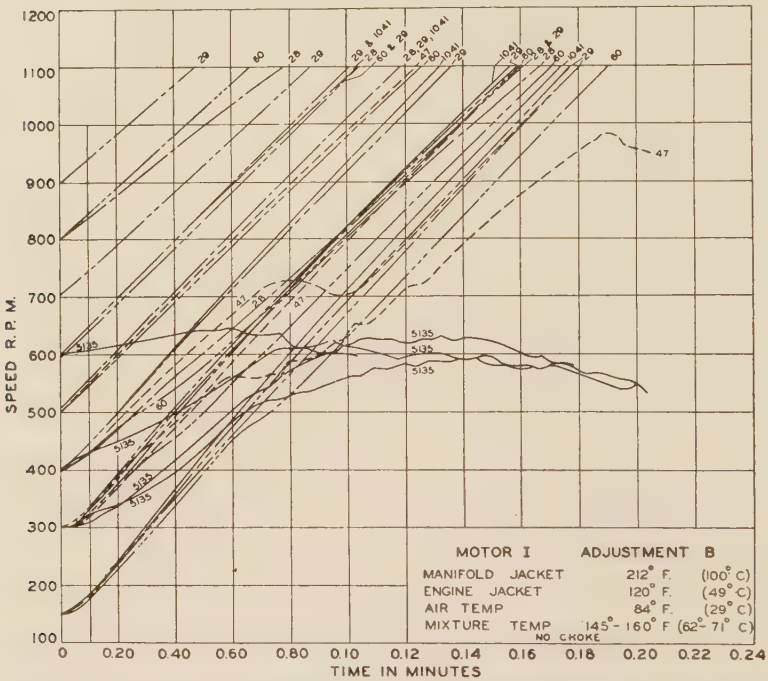

Figure 13—Acceleration Curves Obtained with Motor I with Carburetor Adjusted to Minimize Effect of Accelerating Devices in Enriching the Mixture, with a Warm Motor and Warm Manifold

5160, 28, and 29 when choked to the same extent. These three fuels which cross at about 40 per cent vaporized on the A. S. T. M. distillation gave approximately the same acceleration under the conditions of the tests. This can be quantitatively explained if the non-volatile material contained in fuel 5160 is not burned in the cool motor. Fuels 28 and 29 possess about 60 per cent effective volatility under these conditions and fuel 5160 contains about 40 per cent of heavy ends or about 60 per cent of material efficiently combustible at the temperature of the test.

When no choke is used at an initial speed of 300 or 400

r. p. m., fuel 5160 gives possible performance, but fuels 29 and 28 do not possess sufficient volatility to supply an explosive mixture to the cylinder. This comparison, including a fuel only 65 per cent of which is probably combustible, again emphasizes the importance of the first half of the A. S. T. M. distillation in determining acceleration.

Test on Motor I with Carburetor Adjusted to Minimize Effect of Accelerating Charge

In order to check the interpretation of the different performances obtained with the same fuels on Motors I and II

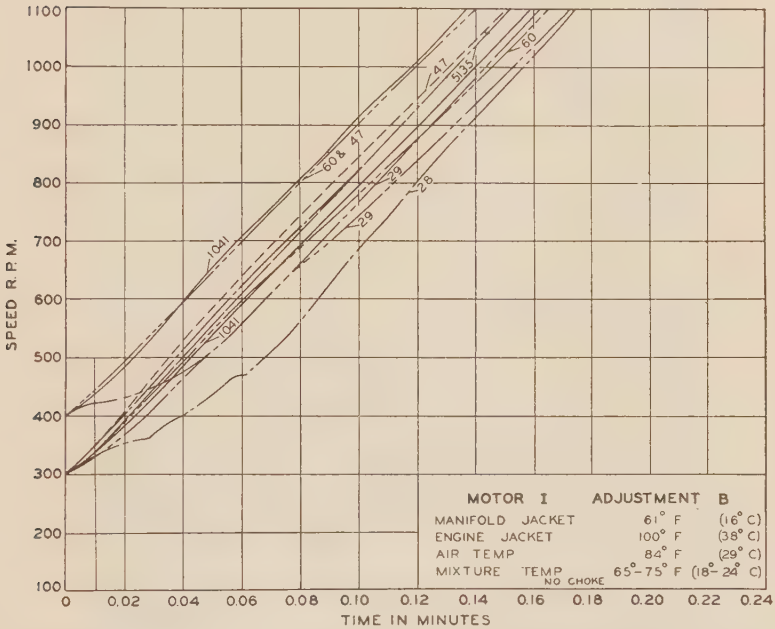

Figure 14—Acceleration Curves Obtained with Motor I with Carburetor Adjusted So as to Minimize Effect of Accelerating Devices in Enriching Mixture, with a Cool Motor and Cool Manifold

as due to metering characteristics of the carburetors, the two series of tests reported in Figures 13 and 14 were run on Motor I with the carburetor adjusted to decrease the action of the air valve in enriching the mixture when the throttle was opened. This was done by installing a weaker spring to operate the air valve and also drilling a hole in the dash pot so that the air valve would open more rapidly when the throttle was opened.

Warm Manifold—In Figure 13 the mixture temperature is approximately 150° F. in most cases. In Figure 16 of Part III it is seen that 65 per cent should be vaporized on the A. S. T. M. distillation at 320° F. if perfect acceleration performance is to be expected. Fuels 28 and 5135 are the only

ones in this series which do not meet this requirement. Also these fuels are the only ones which do not possess sufficient effective volatility to give perfect performance.

Under these conditions with a leaner mixture supplied during the accelerating period, fuels 29 and 60 do not show the decidedly poor performance observed in the earlier tests with this motor. In fact, fuel 29 is only slightly inferior to fuel 1041 at the lower speed and practically equal to 1041 at all speeds above 400 r. p. m. Fuel 60 is considerably more volatile than fuel 29 and shows the characteristic loss in power at the lower speed. Fuel 60, having a 90 per cent point below 320° F., is completely effectively vaporized under these conditions and would be expected to give poorer performance with a mixture ratio of 7 or 8 than fuel 29, which is about 75 per cent effectively vaporized under these conditions.

The poor performance of fuel 28 at the higher speeds is due to its inadequate volatility at 320° F. or its high 70 per cent point, which should be below 320° F. to deliver a mixture ratio of 13 when one of 9 is supplied by the carburetor.

At the lower speeds 5135 gives fair acceleration until the accelerating charge has lost its effect. As indicated by curve *C* in Figure 16 of Part III, 35 per cent at about 300° F. is barely enough volatility to supply an explosive mixture to the cylinders when an air-fuel ratio of 12:1 is supplied by the carburetor.

The irregular performance of fuel 47 at the lower speeds is definitely due to vapor lock, which intermittently shuts off the fuel from the carburetor jet.

Cool Manifold—The data plotted in Figure 14 were obtained with the same carburetor adjustment as was used in obtaining the data in Figure 13, but the engine conditions were modified to represent the warming-up period in cold weather.

According to Figure 16 of Part III, 35 per cent vaporized on the A. S. T. M. distillation at 210° F. should insure satisfactory performance provided the mixture ratio is enriched to about 8:1 during the accelerating period. This is approximately the condition existing at these speeds with this carburetor adjustment. Fuels 1041, 60, 64, and 5135 meet this requirement and give satisfactory performance in all cases. Fuels 28 and 29, which have 35 per cent distilled on the A. S. T. M. distillation at a temperature of about 250° F., give inferior acceleration under these conditions. The data shown in Figure 14 again emphasize the importance of the 35 per cent point on the A. S. T. M. distillation in determining satisfactory performance during the warming-up period.

Fuel 47 at this low mixture temperature gives better acceleration from 300 r. p. m. than any fuel at a mixture temperature of 150° F. This is in accord with general experience that low mixture temperatures give more power and better acceleration provided the fuel possesses the required effective

volatility to deliver a 12:1 air-fuel ratio to the cylinders under the conditions of test.

Comparison of these tests on Motor I with those in which the carburetor was adjusted as delivered from the factory indicate that the relations given in Figure 16 of Part III hold for different speeds, carburetor adjustments, and temperatures, provided only the air-fuel ratio and mixture temperature are known.

Conclusions

The relationship between A. S. T. M. distillation and character of engine performance indicated in Figure 16 of Part III can be applied in an entirely satisfactory manner to estimate engine performance. It is necessary to know the mixture temperature between the hot spot and the cylinder block, the air-fuel ratio supplied by the carburetor during the acceleration period, and the A. S. T. M. distillation curve of the fuel.

The following statements summarize the conclusions regarding motor performance as applied to motor fuel for use in modern automotive equipment:

(1) That part of the A. S. T. M. distillation curve from 65 to 100 per cent is of little or no practical importance in determining effective volatility in modern motors, provided the 90 per cent point is not so high as to prevent efficient combustion of the fuel under the conditions of test, nor so low as to supply a practically dry mixture when used in cars equipped with heated manifolds and effective accelerating devices.

(2) The first 35 to 40 per cent of the A. S. T. M. distillation curve is the controlling factor in determining fairly satisfactory performance without use of the choke, or entirely satisfactory performance with use of the choke, during the warming-up period, provided the conditions stated above concerning the 90 per cent point are fulfilled.

(3) At least 10 per cent must be distilled on the A. S. T. M. distillation at the corresponding indicated temperature in Figure 16 of Part III, if the motor is to be operated in a satisfactory manner even with excessively rich mixtures as brought about by use of the choke with a properly adjusted carburetor. It is possible to operate a motor with the choke on any fuel that will start the cold motor in ten revolutions with an air-fuel ratio of 1:1.

Different metering characteristics possessed by carburetors of different types will modify these conclusions only in degree. This has been brought out in the tests reported for Motors I and II, which represent the practical extremes of modern types of carburetors.

Low 90 per cent points are required for satisfactory performance of aviation motors and other engines in special service where maximum power and freedom from detonation are best obtained with cold mixtures and extremely volatile fuel.

Nothing reported in this investigation should be interpreted to indicate that best performance cannot be obtained with highly volatile fuels provided the motor is designed and

equipped to handle such fuels in an efficient manner. The modern motor car is designed to operate with fuels that are between 45 and 65 per cent effectively vaporized, and unsatisfactory performance is to be expected if the fuel is less than 45 or more than 65 per cent effectively vaporized. These percentages correspond to 35 and 65 per cent on the A. S. T. M. distillation, respectively. For this reason low 35 and 65 per cent points are required for best performance with cool motors, but high 80 and 90 per cent points are required to insure that the fuel will not be completely effectively vaporized, for the best performance of modern motor cars.

By combining the data of Figure 1 of this paper and Figure 16 of Part III as interpreted by the tests reported in this paper, it is possible to suggest the following A. S. T. M. distillation characteristics required for satisfactory motor performance under different atmospheric temperatures. This has been done in Table I for the two extreme types of motors now in use.

Table I—Relation between A. S. T. M. Distillation and Motor Performance at Different Atmospheric Temperatures

Atmos. Temp.	Points on A. S. T. M. Distillation							
	10%		35%		60%		90%	
	Min.	Max.	1/2 Min.	2 Min.	4 Min.	8–10 Min.	Min.	Max.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.	° F.
Car equipped with exhaust-heated manifold hot spot, carburetor with effective accelerating device, and radiator shutters								
80	140	230	235	275	275	320	390	450
50	125	190	200	250	260	310	375	420
20	110	150	175	230	235	290	350	400
−10	90	100	125	210	180	280	320	400
Car not equipped with radiator shutters, and supplying less heat to intake manifold, or with carburetor which supplies only a limited accelerating charge								
			4 Min.		65%			
80	135	230	235	280	...	300	320	450
50	115	190	190	240	...	260	250	410
20	100	150	150	200	...	200	180	390
−10	85	100	100	160	...	120	120	370

Explanations of Columns

(1) Average atmospheric temperature in which the cold motor is started and operated.

(2) The lowest 10 per cent temperature consistent with easy starting of cold motor, and freedom from vapor lock with hot motor.

(3) The highest 10 per cent temperature which allows starting and warming up without difficulty under average conditions.

(4) The maximum 35 per cent temperature which allows possible to fairly satisfactory operation without choking about 1/2 minute after starting, or entirely satisfactory performance with the use of the choke.

(5) The maximum 35 per cent temperature which allows similar operation 2 or 4 minutes after starting.

(6) The maximum 60 or 65 per cent temperature giving almost perfect performance without choking about 4 minutes after starting.

(7) The maximum 60 or 65 per cent temperature giving perfect performance without choking about 8 to 10 minutes after starting.

(8) The minimum 90 per cent temperature not causing loss in acceleration on warm motor.

(9) Maximum temperatures of 90 per cent now known to be satisfactory under indicated conditions.

Literature Cited

(1) Hughes, *J. Soc. Automotive Eng.*, **26**, 49 (1930).
(2) Mock, *Ibid.*, **24**, 598 (1929).